CLAIMS

1.   A computer system configured by stored instructions as a garbage collector that reclaims for reuse memory allocated by a mutator executing on the computer system, wherein the garbage collector:

     A)   repeatedly performs global marking operations on the heap;

     B)   treats the heap as divided into a plurality of heap regions for each of at least some of which the garbage collector so maintains a respective remembered set associated therewith that, independently of which other heap regions contain references to objects in that heap region, entries in that remembered set identify the locations of all such references;

     C)   performs space-incremental-collection operations, associated with respective collection sets, in which the garbage collector employs each remembered set associated with a region in the collection set to determine whether objects in the collection set satisfy a potential-reachability criterion and reclaims memory occupied by objects that do not satisfy the potential-reachability criterion; and

     D)   selects regions for the collection sets by performing calculations of collection-efficiency estimates based at least in part on at least one said global marking operation's results.

2.   A computer system as defined in claim 1 wherein the calculations of the collection-efficiency estimates include, for regions containing only objects allocated at the beginning of the most-recent completed global marking operation, estimating from that global marking operation's results respective amounts of memory likely to be reclaimed if those regions are included in the collection set.

3.   A computer system as defined in claim 2 wherein the global marking operations are performed at least in part concurrently with the mutator's execution.

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4. A computer system as defined in claim 2 wherein the calculations of collection-efficiency estimates include determining which of a set of candidate groups of regions yields the greatest ratio of likely memory reclamation to reclamation cost.

5. A computer system as defined in claim 2 wherein:

A) each of at least some of the global marking operations includes tracing reference chains from a root set and so making marks associated with that global marking operation and with the locations of respective objects thereby encountered that in at least some portions of the heap an object's lack of reachability can be inferred at the end of that global marking operation from the absence of a mark associated with that object's location and that global marking operation; and

B) each of at least some of the space-incremental-collection operations includes:

i) inferring from the marks made by one of the global marking operations that objects in the collection set are unreachable; and

ii) reclaiming the memory space occupied by such objects.

6 A computer system as defined in claim 2 wherein the calculations of the collection-efficiency estimates include, for at least some regions, calculating a cost from the sizes of the remembered sets associated therewith.

7. A computer system as defined in claim 6 wherein:

A) the collector associates respective age values with the regions;

B) the calculations of the collection-efficiency estimates include, for some regions, making estimates, based of those regions' age values, of respective amounts of memory likely to be reclaimed if those regions are included in the remembered set.

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1 8. A computer system as defined in claim 7 wherein:

2 A) the collector calculates, for each of a plurality of the age values, a respec-

3 tive average of how much memory has been reclaimed from regions with

4 which it associates that age value; and`

5 B) the estimates based on the regions' age values are calculated from those

6 averages.

1 9. A computer system as defined in claim 1 wherein the calculations of collection-

2 efficiency estimates include determining which of a set of candidate groups of regions

3 yields the greatest ratio of likely memory reclamation to reclamation cost.

1 10. A computer system as defined in claim 9 wherein:

2 A) each space-incremental-collection operation includes processing d re-

3 membered-set-log-buffer entries, $d \geq 0$, in order to update remembered

4 sets; and

5 B) the reclamation cost $V(cs)$ for a candidate group cs of regions is deter-

6 mined in accordance with

7
$$V(cs) = V_{fixed} + U \cdot d + \sum_{r \in cs} (S \cdot rsSize(r) + C \cdot liveBytes(r)),$$

8 where V_{fixed} represents fixed costs common to all pauses, d is the number

9 of remembered-set-log-buffer entries to be scanned during that space-

10 incremental-collection operation, U is the average cost of scanning a re-

11 membered-set-log-buffer entry, S is the cost per remembered-set entry of

12 scanning a remembered set, $rsSize(r)$ is the number of remembered-set en-

13 tries in the remembered set maintained for region r, C is the cost per byte

14 of evacuating and scanning an object that is not reclaimed, and $live$-

15 $Bytes(r)$ is an estimate of how many bytes will not be reclaimed from re-

16 gion r.

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11. A computer system as defined in claim 1 wherein:

    A) each of at least some of the global marking operations includes tracing reference chains from a root set and so making marks associated with that global marking operation and with the locations of respective objects thereby encountered that in at least some portions of the heap an object's lack of reachability can be inferred at the end of that global marking operation from the absence of a mark associated with that object's location and that global marking operation; and

    B) each of at least some of the space-incremental-collection operations includes:

        i) inferring from the marks made by one of the global marking operations that objects in the collection set are unreachable; and

        ii) reclaiming the memory space occupied by such objects.

12. A computer system as defined in claim 11 wherein the calculations of collection-efficiency estimates include determining which of a set of candidate groups of regions yields the greatest ratio of likely memory reclamation to reclamation cost.

13. A computer system as defined in claim 1 wherein the global marking operations are performed at least in part concurrently with the mutator's execution.

14. A method of employing a computer system to reclaim for reuse memory dynamically allocated from a heap in the computer system's memory by a mutator executing on that computer system, a method comprising:

    A) repeatedly performing global marking operations on the heap;

    B) treating the heap as divided into a plurality of heap regions and, for each of at least some of those heap regions, so maintaining an associated remembered set that, independently of which other heap regions contain ref-

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8   erences to objects in that heap region, entries in that remembered set iden-

9   tify the locations of all such references;

10   C)   performing space-incremental-collection operations, associated with re-

11   spective collection sets, in which each remembered set associated with a

12   region in the collection set is employed to determine whether objects in

13   the collection set satisfy a potential-reachability criterion and reclaims

14   memory occupied by objects that do not satisfy the potential-reachability

15   criterion; and

16   D)   selecting regions for the collection sets by performing calculations of col-

17   lection-efficiency estimates based at least in part on at least one said

18   global marking operation's results.

1   15.   A method as defined in claim 14 wherein the calculations of the collection-

2   efficiency estimates include, for regions containing only objects allocated at the begin-

3   ning of the most-recent completed global marking operation, estimating from that global

4   marking operation's results respective amounts of memory likely to be reclaimed if those

5   regions are included in the collection set.

1   16.   A method as defined in claim 15 wherein the global marking operations are per-

2   formed at least in part concurrently with the mutator's execution.

1   17.   A method as defined in claim 15 wherein the calculations of collection-efficiency

2   estimates include determining which of a set of candidate groups of regions yields the

3   greatest ratio of likely memory reclamation to reclamation cost.

1   18.   A method as defined in claim 15 wherein:

2   A)   each of at least some of the global marking operations includes tracing ref-

3   erence chains from a root set and so making marks associated with that

4   global marking operation and with the locations of respective objects

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5   thereby encountered that in at least some portions of the heap an object's

6   lack of reachability can be inferred at the end of that global marking op-

7   eration from the absence of a mark associated with that object's location

8   and that global marking operation; and

9   B)   each of at least some of the space-incremental-collection operations in-

10   cludes:

11   i)   inferring from the marks made by one of the global marking opera-

12   tions that objects in the collection set are unreachable; and

13   ii)   reclaiming the memory space occupied by such objects.

1   19   A method as defined in claim 15 wherein the calculations of the collection-

2 efficiency estimates include, for at least some regions, calculating a cost from the sizes of

3 the remembered sets associated therewith.

1   20.   A method as defined in claim 19 wherein:

2   A)   the method further includes associating respective age values with the re-

3   gions;

4   B)   the calculations of the collection-efficiency estimates include, for some

5   regions, making estimates, based of those regions' age values, of respec-

6   tive amounts of memory likely to be reclaimed if those regions are in-

7   cluded in the remembered set.

1   21.   A method as defined in claim 20 wherein:

2   A)   the method further includes calculating, for each of a plurality of the age

3   values, a respective average of how much memory has been reclaimed

4   from regions with which that age value is associated; and

5   B)   the estimates based on the regions' age values are calculated from those

6   averages.

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1   22.   A method as defined in claim 14 wherein the calculations of collection-efficiency

2   estimates include determining which of a set of candidate groups of regions yields the

3   greatest ratio of likely memory reclamation to reclamation cost.

1   23.   A method as defined in claim 22 wherein:

2   A)   each space-incremental-collection operation includes processing d re-

3   membered-set-log-buffer entries, $d \geq 0$, in order to update remembered

4   sets; and

5   B)   the reclamation cost $V(cs)$ for a candidate group cs of regions is deter-

6   mined in accordance with

7    $$V(cs) = V_{fixed} + U \cdot d + \sum_{r \in cs}(S \cdot rsSize(r) + C \cdot liveBytes(r)),$$

8   where V_{fixed} represents fixed costs common to all pauses, d is the number

9   of remembered-set-log-buffer entries to be scanned during that space-

10   incremental-collection operation, U is the average cost of scanning a re-

11   membered-set-log-buffer entry, S is the cost per remembered-set entry of

12   scanning a remembered set, $rsSize(r)$ is the number of remembered-set en-

13   tries in the remembered set maintained for region r, C is the cost per byte

14   of evacuating and scanning an object that is not reclaimed, and *live-*

15   *Bytes(r)* is an estimate of how many bytes will not be reclaimed from re-

16   gion r.

1   24.   A method as defined in claim 14 wherein:

2   A)   each of at least some of the global marking operations includes tracing ref-

3   erence chains from a root set and so making marks associated with that

4   global marking operation and with the locations of respective objects

5   thereby encountered that in at least some portions of the heap an object's

6   lack of reachability can be inferred at the end of that global marking op-

7   eration from the absence of a mark associated with that object's location

8   and that global marking operation; and

9   B)   each of at least some of the space-incremental-collection operations in-

10   cludes:

11   i)   inferring from the marks made by one of the global marking opera-

12   tions that objects in the collection set are unreachable; and

13   ii)   reclaiming the memory space occupied by such objects.

1   25.   A method as defined in claim 24 wherein the calculations of collection-efficiency

2   estimates include determining which of a set of candidate groups of regions yields the

3   greatest ratio of likely memory reclamation to reclamation cost.

1   26.   A method as defined in claim 14 wherein the global marking operations are per-

2   formed at least in part concurrently with the mutator's execution.

1   27.   A storage medium containing instructions readable by a computer system to con-

2   figure the computer system as a garbage collector that reclaims for reuse memory allo-

3   cated by a mutator executing on the computer system, wherein the garbage collector:

4   A)   repeatedly performs global marking operations on the heap;

5   B)   treats the heap as divided into a plurality of heap regions for each of at

6   least some of which the garbage collector so maintains a respective re-

7   membered set associated therewith that, independently of which other

8   heap regions contain references to objects in that heap region, entries in

9   that remembered set identify the locations of all such references;

10   C)   performs space-incremental-collection operations, associated with respec-

11   tive collection sets, in which the garbage collector employs each remem-

12   bered set associated with a region in the collection set to determine

13   whether objects in the collection set satisfy a potential-reachability crite-

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14   rion and reclaims memory occupied by objects that do not satisfy the po-

15   tential-reachability criterion; and

16   D)   selects regions for the collection sets by performing calculations of collec-

17   tion-efficiency estimates based at least in part on at least one said global

18   marking operation's results.

1   28.   A storage medium as defined in claim 29 wherein the calculations of the collec-

2   tion-efficiency estimates include, for regions containing only objects allocated at the be-

3   ginning of the most-recent completed global marking operation, estimating from that

4   global marking operation's results respective amounts of memory likely to be reclaimed

5   if those regions are included in the collection set.

1   29.   A storage medium as defined in claim 28 wherein the global marking operations

2   are performed at least in part concurrently with the mutator's execution.

1   30.   A storage medium as defined in claim 28 wherein the calculations of collection-

2   efficiency estimates include determining which of a set of candidate groups of regions

3   yields the greatest ratio of likely memory reclamation to reclamation cost.

1   31.   A storage medium as defined in claim 28 wherein:

2   A)   each of at least some of the global marking operations includes tracing ref-

3   erence chains from a root set and so making marks associated with that

4   global marking operation and with the locations of respective objects

5   thereby encountered that in at least some portions of the heap an object's

6   lack of reachability can be inferred at the end of that global marking op-

7   eration from the absence of a mark associated with that object's location

8   and that global marking operation; and

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9 B) each of at least some of the space-incremental-collection operations in-

10 cludes:

11 i) inferring from the marks made by one of the global marking opera-

12 tions that objects in the collection set are unreachable; and

13 ii) reclaiming the memory space occupied by such objects.

1 32 A storage medium as defined in claim 28 wherein the calculations of the collec-

2 tion-efficiency estimates include, for at least some regions, calculating a cost from the

3 sizes of the remembered sets associated therewith.

1 33. A storage medium as defined in claim 32 wherein:

2 A) the collector associates respective age values with the regions;

3 B) the calculations of the collection-efficiency estimates include, for some

4 regions, making estimates, based of those regions' age values, of respec-

5 tive amounts of memory likely to be reclaimed if those regions are in-

6 cluded in the remembered set.

1 34. A storage medium as defined in claim 33 wherein:

2 A) the collector calculates, for each of a plurality of the age values, a respec-

3 tive average of how much memory has been reclaimed from regions with

4 which it associates that age value; and

5 B) the estimates based on the regions' age values are calculated from those

6 averages.

1 35. A storage medium as defined in claim 27 wherein the calculations of collection-

2 efficiency estimates include determining which of a set of candidate groups of regions

3 yields the greatest ratio of likely memory reclamation to reclamation cost.

1 36. A storage medium as defined in claim 35 wherein:

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2   A)   each space-incremental-collection operation includes processing d re-

3   membered-set-log-buffer entries, $d \geq 0$, in order to update remembered

4   sets; and

5   B)   the reclamation cost $V(cs)$ for a candidate group cs of regions is deter-

6   mined in accordance with

7

$$V(cs) = V_{fixed} + U \cdot d + \sum_{r \in cs} (S \cdot rsSize(r) + C \cdot liveBytes(r)),$$

8   where V_{fixed} represents fixed costs common to all pauses, d is the number

9   of remembered-set-log-buffer entries to be scanned during that space-

10   incremental-collection operation, U is the average cost of scanning a re-

11   membered-set-log-buffer entry, S is the cost per remembered-set entry of

12   scanning a remembered set, $rsSize(r)$ is the number of remembered-set en-

13   tries in the remembered set maintained for region r, C is the cost per byte

14   of evacuating and scanning an object that is not reclaimed, and *live-*

15   *Bytes*(r) is an estimate of how many bytes will not be reclaimed from re-

16   gion r.

1   37.   A storage medium as defined in claim 27 wherein:

2   A)   each of at least some of the global marking operations includes tracing ref-

3   erence chains from a root set and so making marks associated with that

4   global marking operation and with the locations of respective objects

5   thereby encountered that in at least some portions of the heap an object's

6   lack of reachability can be inferred at the end of that global marking op-

7   eration from the absence of a mark associated with that object's location

8   and that global marking operation; and

9   B)   each of at least some of the space-incremental-collection operations in-

10   cludes:

11   i)   inferring from the marks made by one of the global marking opera-

12   tions that objects in the collection set are unreachable; and

13   ii)   reclaiming the memory space occupied by such objects.

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1   38.   A storage medium as defined in claim 37 wherein the calculations of collection-

2   efficiency estimates include determining which of a set of candidate groups of regions

3   yields the greatest ratio of likely memory reclamation to reclamation cost.

1   39.   A storage medium as defined in claim 27 wherein the global marking operations

2   are performed at least in part concurrently with the mutator's execution.

1   40.   An electromagnetic signal representing instructions readable by a computer sys-

2   tem to configure the computer system as a garbage collector that reclaims for reuse mem-

3   ory allocated by a mutator executing on the computer system, wherein the garbage collec-

4   tor:

5   A)   repeatedly performs global marking operations on the heap;

6   B)   treats the heap as divided into a plurality of heap regions for each of at

7   least some of which the garbage collector so maintains a respective re-

8   membered set associated therewith that, independently of which other

9   heap regions contain references to objects in that heap region, entries in

10   that remembered set identify the locations of all such references;

11   C)   performs space-incremental-collection operations, associated with respec-

12   tive collection sets, in which the garbage collector employs each remem-

13   bered set associated with a region in the collection set to determine

14   whether objects in the collection set satisfy a potential-reachability crite-

15   rion and reclaims memory occupied by objects that do not satisfy the po-

16   tential-reachability criterion; and

17   D)   selects regions for the collection sets by performing calculations of collec-

18   tion-efficiency estimates based at least in part on at least one said global

19   marking operation's results.

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1   41.   An electromagnetic signal as defined in claim 42 wherein the calculations of the

2   collection-efficiency estimates include, for regions containing only objects allocated at

3   the beginning of the most-recent completed global marking operation, estimating from

4   that global marking operation's results respective amounts of memory likely to be re-

5   claimed if those regions are included in the collection set.

1   42.   An electromagnetic signal as defined in claim 41 wherein the global marking op-

2   erations are performed at least in part concurrently with the mutator's execution.

1   43.   An electromagnetic signal as defined in claim 41 wherein the calculations of col-

2   lection-efficiency estimates include determining which of a set of candidate groups of

3   regions yields the greatest ratio of likely memory reclamation to reclamation cost.

1   44.   An electromagnetic signal as defined in claim 41 wherein:

2   A)   each of at least some of the global marking operations includes tracing ref-

3   erence chains from a root set and so making marks associated with that

4   global marking operation and with the locations of respective objects

5   thereby encountered that in at least some portions of the heap an object's

6   lack of reachability can be inferred at the end of that global marking op-

7   eration from the absence of a mark associated with that object's location

8   and that global marking operation; and

9   B)   each of at least some of the space-incremental-collection operations in-

10   cludes:

11   i)   inferring from the marks made by one of the global marking opera-

12   tions that objects in the collection set are unreachable; and

13   ii)   reclaiming the memory space occupied by such objects.

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1   45   An electromagnetic signal as defined in claim 41 wherein the calculations of the

2   collection-efficiency estimates include, for at least some regions, calculating a cost from

3   the sizes of the remembered sets associated therewith.

1   46.   An electromagnetic signal as define in claim 45 wherein:

2   A)   the collector associates respective age values with the regions;

3   B)   the calculations of the collection-efficiency estimates include, for some

4   regions, making estimates, based of those regions' age values, of respec-

5   tive amounts of memory likely to be reclaimed if those regions are in-

6   cluded in the remembered set.

1   47.   An electromagnetic signal as define in claim 46 wherein:

2   A)   the collector calculates, for each of a plurality of the age values, a respec-

3   tive average of how much memory has been reclaimed from regions with

4   which it associates that age value; and

5   B)   the estimates based on the regions' age values are calculated from those

6   averages.

1   48.   An electromagnetic signal as defined in claim 40 wherein the calculations of col-

2   lection-efficiency estimates include determining which of a set of candidate groups of

3   regions yields the greatest ratio of likely memory reclamation to reclamation cost.

1   49.   An electromagnetic signal as defined in claim 48 wherein:

2   A)   each space-incremental-collection operation includes processing d re-

3   membered-set-log-buffer entries, $d \geq 0$, in order to update remembered

4   sets; and

5   B)   the reclamation cost $V(cs)$ for a candidate group cs of regions is deter-

6   mined in accordance with

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$$V(cs) = V_{fixed} + U \cdot d + \sum_{recs} (S \cdot rsSize(r) + C \cdot liveBytes(r)),$$

8   where V_{fixed} represents fixed costs common to all pauses, d is the number

9   of remembered-set-log-buffer entries to be scanned during that space-

10   incremental-collection operation, U is the average cost of scanning a re-

11   membered-set-log-buffer entry, S is the cost per remembered-set entry of

12   scanning a remembered set, $rsSize(r)$ is the number of remembered-set en-

13   tries in the remembered set maintained for region r, C is the cost per byte

14   of evacuating and scanning an object that is not reclaimed, and *live-*

15   *Bytes*(r) is an estimate of how many bytes will not be reclaimed from re-

16   gion r.

1   50.   An electromagnetic signal as defined in claim 40 wherein:

2   A)   each of at least some of the global marking operations includes tracing ref-

3   erence chains from a root set and so making marks associated with that

4   global marking operation and with the locations of respective objects

5   thereby encountered that in at least some portions of the heap an object's

6   lack of reachability can be inferred at the end of that global marking op-

7   eration from the absence of a mark associated with that object's location

8   and that global marking operation; and

9   B)   each of at least some of the space-incremental-collection operations in-

10   cludes:

11   i)   inferring from the marks made by one of the global marking opera-

12   tions that objects in the collection set are unreachable; and

13   ii)   reclaiming the memory space occupied by such objects.

1   51.   An electromagnetic signal as defined in claim 50 wherein the calculations of col-

2   lection-efficiency estimates include determining which of a set of candidate groups of

3   regions yields the greatest ratio of likely memory reclamation to reclamation cost.

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1   52.   An electromagnetic signal as defined in claim 40 wherein the global marking op-

2   erations are performed at least in part concurrently with the mutator's execution.

1   53.   For employing a computer system to reclaim for reuse memory dynamically allo-

2   cated from a heap in the computer system's memory by a mutator executing on that com-

3   puter system, a garbage collector comprising:

4   A)   means for repeatedly performing global marking operations on the heap;

5   B)   means for treating the heap as divided into a plurality of heap regions and,

6   for each of at least some of those heap regions, so maintaining an associ-

7   ated remembered set that, independently of which other heap regions con-

8   tain references to objects in that heap region, entries in that remembered

9   set identify the locations of all such references;

10   C)   means for performing space-incremental-collection operations, associated

11   with respective collection sets, in which each remembered set associated

12   with a region in the collection set is employed to determine whether ob-

13   jects in the collection set satisfy a potential-reachability criterion and re-

14   claims memory occupied by objects that do not satisfy the potential-

15   reachability criterion; and

16   D)   means for selecting regions for the collection sets by performing calcula-

17   tions of collection-efficiency estimates based at least in part on at least one

18   said global marking operation's results.

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